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Accuracy of Teleseismic Event Locations in the Middle East and North Africa

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Abstract

Seismic characterization at the regional level requires accurate determination of phases and travel times for many combinations of stations and events. An important consideration in the process is the accuracy of event locations. The LLNL Comprehensive Test Ban Treaty Research Program is currently working on data from the Middle East and North Africa, where seismic station coverage is relatively sparse and "ground truth" seismic source information is practically nonexistent. In this report I use aftershock studies as a source of local ground truth. I evaluate teleseismic location accuracy by comparing hypocenters determined by local networks with those determined teleseismically [e.g. the International Seismological Center (ISC) and the National Earthquake Information Center (NEIC)]. Epicentral locations, origin times, and depth determinations of events from three aftershocks studies (Algeria, Armenia, and Iran) and one local network study (Iran) are compared with ISC and NEIC locations for the same events. The key parameter for the ISC locations is the number of observations used in the location determination. For more than 40-50 observations (or stations), corresponding to an ISC M_b of 4.4-4.5, ISC locations differ by less than 10-15 km from local network locations. With fewer than 40-50 observations, the agreement rapidly diminishes and ISC locations can differ from local determinations by as much as 80 km or more. Events in Iran show a distinct bias of ISC location errors toward the northeast; events in Armenia and Algeria show no directional bias. This study shows that only events with ISC M_b > 4.4-4.5 or NEIS M_b > 4.7-4.8 should be used for compiling travel time information from teleseismic bulletins in the Middle East/North Africa region when locations from the NEIC and ISC bulletins are used.

Introduction

The Comprehensive Test Ban Treaty Research Program at Lawrence Livermore National Laboratory (LLNL) is carrying out research to support US worldwide seismic monitoring efforts. Methods developed and data acquired under these efforts will eventually be used by the National Data Center (NDC), which will conduct monitoring for the Comprehensive Test Ban Treaty (CTBT). Current activities at LLNL are focused on the characterization of seismic propagation and evaluation of discriminant measures in the Middle East and North Africa (MENA) region (roughly the area encompassing the countries of Morocco, Algeria, Libya, Egypt, the Saudi Arabian peninsula, the Levant, Turkey, Iran, Iraq, and Syria). The goal of the project is to maximize the ability to locate events and to perform discrimination analysis (determine if the event is an earthquake, chemical explosion, or nuclear explosion) using regionally-located seismic arrays. The work is focused on MENA but not limited exclusively to it; some data may extend into outlying regions.

A key component of seismic characterization is the measurement of the travel times of regional seismic phases (P_n, P_g, S_n, L_g) from events located at a range of distance and azimuth relative to the receiver station or array. The travel time data is then compared to global travel time models [such as IASP91 --Kennett and Engdahl (1991)] to make regional corrections for local variations due to geologic structure. In order to obtain accurate travel time residuals one must be certain that the events used in the calibration are well located (location errors < 10-20 km). Thus "ground truth", i.e. accurate local information about event locations, is extremely important for

regional seismic characterization. Controlled explosion sources provide ideal ground truth because their location and origin time can be precisely determined. Lacking such events and data from local catalogs, the next best ground truth available comes from aftershock studies.

A relatively common procedure in earthquake hazard studies is the practice of monitoring aftershocks of large damaging earthquakes. In such studies, local arrays of seismic instruments are set up around the epicenter of the earthquake to monitor and locate aftershocks which characterize the shape of the fault plane and the nature of slip. These studies are important for assessing future damage potential of the fault, measuring the moment and tectonic release of the earthquake, and in defining the seismotectonics of the region. If the local array is properly configured, hypocenters of local events of very low magnitude can be determined with errors as low as 1 km or less. These well-located events from the local array provide excellent ground truth for that region. In addition, inversion of local travel times of the aftershocks allows determination of an accurate velocity model of the crust in the vicinity of the events.

For this study I have researched published literature for reports of aftershock studies, or studies involving relocations of earthquakes based on local networks, in the Middle East and North Africa region. To date I have found four such studies from Iran, Algeria, and Armenia with aftershocks also reported in the International Seismic Center (ISC) event bulletin. The rest of this report consists of an analysis of the data from these studies, comparison with ISC and National Earthquake Information Center (NEIC) locations, and a discussion of the results.

Events in Iran

Berberian (1979b) compared the accuracy of teleseismic epicenters with the macroscopic (determined from surface ground breakage or damage assessments) epicenters of large magnitude events in Iran as a function of time as more instruments were added to the worldwide network of seismic stations. His figure 2 showed that the mean error of ISS-ISC locations compared to macroseismic epicenters was as high as 100 km prior to 1930, decreasing to about 15 km by 1979. The error of 15 km represents his assessment of the mean error in teleseismic locations of events of M_b 6.0 and higher with an instrumental system similar to that of the present ISC network. Additional studies (Asudeh, 1983; Berberian, 1979a; Berberian, 1984) also point out that location errors for earthquakes in Iran can be quite large.

A local study in the Kermanshah region at the northwestern end of the Zagros Main Thrust by Niazi et al. (1978) showed that there are often large errors in event locations in Iran, especially in the Zagros mountain range and for smaller events. In a more comprehensive study, Jackson (1980) used a plot of the number of ISC station P-phase determinations for an event location versus the ISC focal depth to demonstrate that events with depths greater than 70-80 km were found only when the number of stations was less than 100. This suggests that smaller events may have large errors in depth determination. In the paper, Jackson also states that "...nobody has identified a pP phase below 60-70 km in the Zagros"; thus reliable data shows that seismicity occurs mainly above the Moho in the Zagros mountain belt and that claims for the occurrence of subduction beneath Zagros are suspect. What is true for the Zagros region doesn't apply to the Makran region; Jackson (1980) noted that a relatively large earthquake located at a depth of 110 km in the Makran region (where subduction of oceanic crust is occurring) is probably accurately located.

In a study by Asudeh (1983), seven earthquakes were re-located using P-wave arrival data from local stations and the assumption of 30 km focal depth with a crustal model revised from the Jeffreys-Bullen model used by the ISC (Adams, 1992). Table II of Asudeh's paper lists the origin

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time and location of the relocated events and compares these with the location and origin times determined by the ISC. Also included in Asudeh's table is the ISC focal depth, a local magnitude determination, the ISC magnitude, the number of local stations used, the number of stations used in the ISC determination, and the horizontal difference in location. I used the locations from Table II of Asudeh (1983) to recalculate the difference in location using the LLNL Seismic Analysis Code (SAC). These calculated distances are slightly different from those of Asudeh. Two of the events in Asudeh's Table II had differences in location of more than 200 km compared to the local network and I did not use these. The remaining five events that I compared to the ISC locations are listed in Table 1. Also listed in Table 1 are locations determined by the NEIC from the Preliminary Determination of Epicenters (PDE) catalog. ISC - local network location differences vary from 7.2 km to 107.6 km, with the largest differences in location being for events with the smallest number of ISC stations (and the lowest magnitude). Note that two of the events well located by the ISC, with 108 and 194 stations, have focal depth determinations of 60 km and 53 km, respectively. Origin times can differ by up to 5 seconds for the more poorly-located events. These well-located events are somewhat deep for earthquakes in Zagros, according to Jackson and Fitch (1981). The NEIC events seem to show better agreement with Asudeh's locations, especially in depth and considering that fewer stations were used. Figure 1 shows a plot, similar to Fig. 3 of Asudeh (1983), of the difference in location between the Asudeh relocations and the ISC locations. In Fig. 1 (and similar figures to follow) I have scaled symbol size of the relocated events (white circles) by the local network ISC M_b to demonstrate that smaller events have much larger location errors than the larger events. More will be said about this in the Discussion section below. Figure 1 shows that events of M_b 4.0 or smaller can have location errors of as much as 100 km. This small set of relocations suggests that there is a spacial bias to the ISC locations, which puts them to the northeast of their true location. The azimuthal gap for the ISC events is listed in the last column on the right of Table 1. (The NEIC PDE bulletin does not list the reporting stations, and hence there is no back azimuth information.) For Zagros, the azimuthal gaps indicate poor station coverage in the region southeast to southwest of the events. Most of the reporting stations are in Europe, to the west-northwest and northern Asia, to the northeast.

In another study in Iran, a temporary array of seismic instruments was deployed by Cambridge University in the epicentral region of the 1978 Tabas-e-Golshan M_s 7.4 earthquake, in which over 20,000 people were killed. Details of the deployment and an assessment of the local tectonics are given by Berberian (1984). Many of the aftershocks from this earthquake were recorded by the Iranian Long Period Array (ILPA) which was operational near Tehran in 1978-1979. A collection of events from the ILPA dataset has been assembled by Multimax, Inc. (see http://www.multimax.com/~gtdb on the internet). Berberian's thesis, Berberian (1981), contains a listing of 329 well located events (his Table V.4). Out of this listing, I found six events that are also listed in the ISC catalog. Of these six, four are also contained in the Multimax, Inc. ILPA listing. Table 2 compares ISC and Cambridge network locations, origin times, and depth determinations for these events. None of these events are listed in the NEIC PDE catalog. ISC magnitudes (M_b) of the events vary from 4.2 (lower values were estimated from the network local magnitudes) to 4.9. Differences in location range from 9 km to 86.7 km; differences in origin time range from 2.3 s to 10.9 s. ISC depths are mostly indeterminate (listed as 33 km) with the network depth determinations ranging from 8.3 km to 30 km with a cluster around 12 km depth. Figure 2, a plot with the same format as Fig. 1, shows that the ISC locations have a bias toward the NNE-NE relative to the network locations; this is similar to what was seen for the Asudeh relocations. The

azimuthal gap for the Tabas events is similar to Zagros, with poor station coverage to the south. Again, the smaller events (in this case events with $M_b < 4.5$) show the largest ISC location differences. The aftershock listing of Berberian (1981) provides a particularly valuable ground truth dataset because many of the aftershocks not listed in the ISC bulletin were also recorded by ILPA and the waveform data for these events are available for analysis.

An aftershock study in Algeria

After the October 1980 El Asnam, Algeria M_s 7.3 earthquake, a portable network of 28 stations was used to monitor aftershocks for 5 weeks (Yielding et al., 1989). A total of 4517 aftershocks were located in the Yielding et al. study. For this study, I used the 91 events listed in Appendix 3 of Yielding et al. (1989), which is a subset for which fault plane solutions were obtained. All of the 91 events had depth determinations which were less than 10 km, with mainly thrust and strike-slip mechanisms. Magnitudes (locally determined using HYPOINVERSE) of the 91 events ranged from 1.87 to 4.25. A total of eight of these events had locations determined by the ISC and three events had locations determined by the NEIC. A comparison of the ISC, NEIC, and local network locations of the eight events is given in Table 3 and Fig. 3.

Note that some ISC magnitudes, when determined, show large departures from the local magnitudes. I have not included a comparison of origin times in Table 3 because Yielding et al. (1989) listed the network origin times only to the minute. Differences in location range from 87.2 km to 1.9 km; both of these extremes occur for relatively small events. In this case some of the events well located by the ISC are also small events, but other small events can show great differences in location. The NEIC locations generally are comparable to the ISC locations, usually with fewer stations used by the NEIC. In this case, for Algeria (Fig. 3), there appears to be no azimuthal bias to the location differences as was seen in Iran. Poorest azumuthal station coverage appears to be toward the southeast, which is toward the African continent and Indian Ocean.

An Aftershock Study in Armenia

An aftershock study of the December 1988 Spitak, Armenia, M_s 6.9 earthquake was reported by Dorbath et al. (1992). As was the case with the El Asnam earthquake, this earthquake sequence consisted of shallow thrust fault events with depths less than 10 km. During the study, a 100 Kg explosion was used to calibrate upper crustal velocities. The aftershock study and the calibration data were used with a master event method to relocate the main shock and a series of aftershocks. Of the 76 relocated aftershocks listed in Table 4 of the Dorbath et al. paper, 13 were also listed in the ISC Bulletin and 11 in the NEIC PDE catalog. A comparison of the network, ISC, and NEIC locations and origin times is given in Table 4 and Fig. 4 below. The ISC magnitudes varied from M_b 4.2 to 4.8. Differences in origin time between the ISC and network determinations range from 0.6 to 14.5 s, with epicentral differences ranging from 4.8 to 105.3 km. In most cases, the NEIC locations are farther from the local network locations than are the ISC locations, although the origin times agree more closely. There are always fewer stations used in the NEIC determinations than for the ISC determinations. As Fig. 4 shows, there is no strong azimuthal bias to the location differences. In general, the largest events show the least difference in location, although one small event shows a small difference as well.

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Table 1: Comparison of regional network, ISC, and NEIC locations for earthquakes in the Zagros region (after Asudeh, 1983)

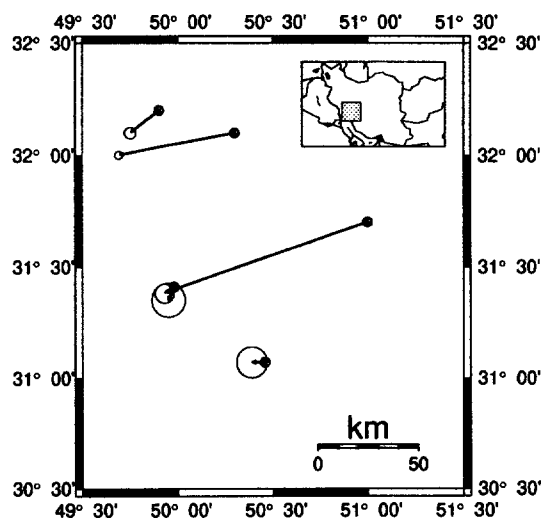| Event ID	Source	Origin Time (h m s)	Lat	Lon	Depth (km)	M_b	Origin time diff. (s)	Epicen-tral diff. (km)	No. of sta-tions	Max. Az. gap (range)
760902a	network	12 17 29.6	32.1N	49.75E	30	3.9				
	ISC	12 17 35	32.2N	49.9E	--	--	5.4	18	4	139°-312°
760902b	network	22 18 29.6	32.0N	49.69E	30	3.7				
	ISC	22 18 35	32.1N	50.3E	33	--	5.4	58.7	4	141°-311°
760905	network	16 43 17.3	31.35N	49.95E	30	4.8				
	ISC	16 43 16.8	31.41N	49.98E	53	5.1	-0.5	7.2	194	128°-180°
	NEIC	16 43 15.8	31.43N	49.97E	44	5.1	-1.5	9.2	95	
760906	network	16 04 45.7	31.07N	50.39E	30	4.7				
	ISC	16 04 47.3	31.07N	50.46E	60	4.9	1.6	6.7	108	128°-201°
	NEIC	16 04 45.1	31.13N	50.37E	39	5.0	-0.6	6.5	51	
760910	network	11 55 19	31.3N	49.93E	30	4.3				
	ISC	11 55 22	31.7N	51.0E	129	3.7	3.0	107.6	11	4°-147°
	NEIC	11 55 16.4	31.57N	49.78E	33	4.0	-2.6	25.5	8	

Figure 1. Relocation of earthquakes in the Zagros region of Iran (see inset), after Asudeh (1983). Shaded circles are ISC locations, white circles are relocations by Asudeh from regional network data and assuming a 30 km focal depth. White circle diameter is scaled by the square of the regional network magnitude (which ranges from M_b 3.7 to 4.9).

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Table 2: Comparison of local network and ISC locations for aftershocks of the Tabas-e-Golshan, Iran, earthquake (after Berberian, 1981).

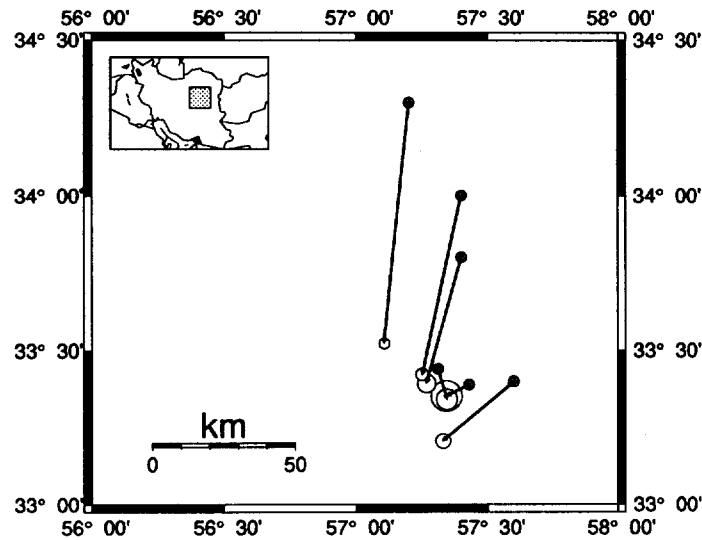| Event ID	Source	Origin Time (h m s)	Lat	Lon	Depth (km)	M_b	Origin time diff. (s)	Epicentral diff. (km)	No. of stations	Max. Az. gap (range)
781001	network	10 49 47.5	33.42N	57.25E	12.6	3.1				
	ISC	10 49 55	34.0N	57.4E	33	4.3	7.5	65.5	10	124°-225°
781009a	network	00 42 43.5	33.21N	57.33E	30.0	3.7				
	ISC	00 42 53	33.4N	57.6E	33	4.4	9.5	33.1	12	125°-230°
781009b	network	16 04 37.0	33.34N	57.34E	18.0	3.7				
	ISC	16 04 43	33.44N	57.31E	46	4.6	6.0	11.3	46	137°-228°
781012	network	15 01 38.7	33.35N	57.34E	11.3	4.0				
	ISC	15 01 41	33.39N	57.43E	18	4.9	2.3	9.0	77	133°-230°
781016	network	21 16 56.9	33.39N	57.27E	8.3	3.5				
	ISC	21 17 05	33.8N	57.4E	33	--	8.1	46.6	8	118°-226°
781019	network	14 39 56.1	33.52N	57.11E	11.9	3.1				
	ISC	14 40 07	34.3N	57.2E	33	--	10.9	86.7	5	95°-222°

Figure 2. Comparison of locations of aftershocks of the Tabas-e-Golshan earthquake. Small shaded circles are ISC locations. White circles are locations determined from the local network (refer to Table 2) and scaled by ISC magnitude as in Fig. 1 (M_b range is 4.2-4.9 — two indeterminate ISC magnitudes were estimated by comparison with the local magnitudes).

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Table 3: Comparison of local network, ISC, and NEIC locations for aftershocks of the El Asnam, Algeria, earthquake (after Yielding et al., 1989).

| Event ID	Source	Origin Time (h m s)	Lat	Lon	Depth (km)	M_b	Origin time diff. (s)	Epicentral diff. (km)	No. of stations	Max. Az. gap (range)
801029	network	01 30 00	36.34N	1.72E	5.49	4.15				
	ISC	01 30 09.8	36.4N	1.77E	10	4.2		8.5	41	73°-231°
	NEIC	01 30 11.2	36.41N	1.58E	10	4.4		14.9	10	
801030	network	00 23 38	36.36N	1.69E	4.56	3.74				
	ISC	00 23 38.1	36.36N	1.65E	1	5.3		3.7	280	85°-132°
	NEIC	07 54 18.2	36.11N	1.36E	10	5.3		4.8	143	
801108	network	07 54 00	36.14N	1.40E	5.47	4.08				
	ISC	07 54 17.4	36.12N	1.38E	4	5.4		2.4	305	163°-183°
801109	network	18 30 00	36.46N	1.63E	6.32	4.18				
	ISC	18 30 43	36.3N	1.8E	0	--		23.2	5	356°-232°
801111	network	01 29 00	36.45N	1.63E	6.33	3.74				
	ISC	01 29 15	36.45N	1.71E	0	--		7.3	10	27°-231°
801115	network	00 12 00	36.22N	1.67E	6.48	3.56				
	ISC	00 12 12.3	36.7N	0.9E	0	--		87.2	6	2°-225°
801110a	network	22 28 00	36.32N	1.64E	4.54	3.51				
	ISC	22 28 44.7	36.13N	1.41E	--	--		29.1	3	313°-231°
801110b	network	21 08 00	36.12N	1.39E	6.35	3.49				
	ISC	21 08 49.5	36.13N	1.41E	--	--		1.9	4	313°-231°
801108	network	02 06 00	36.46N	1.62E	4.46	3.83				
	ISC	02 06 58.5	36.56N	1.59E	--	--		11.8	178	94°-143°
	NEIC	02 06 58.3	36.51N	1.59E	10	4.6		6.7	73	
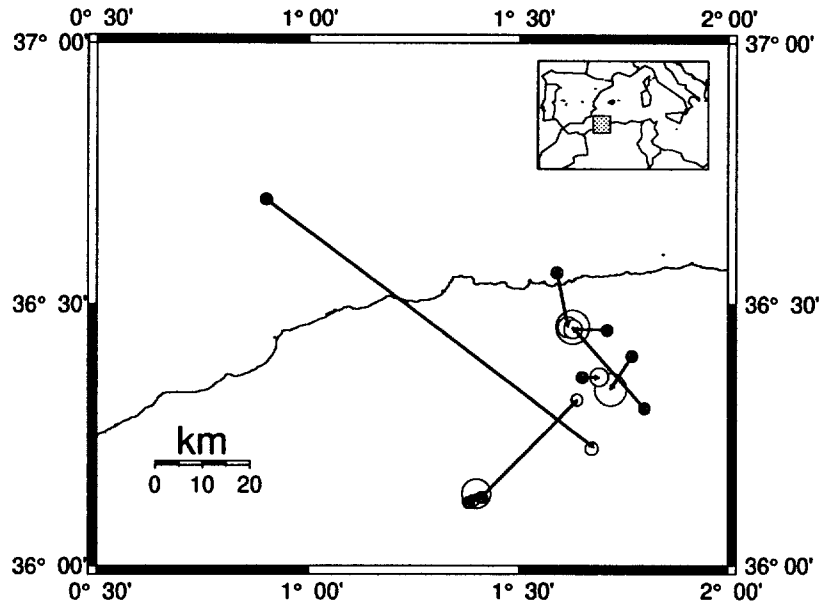
Figure 3. Comparison of locations of aftershocks of the El Asnam earthquake. Small shaded circles are ISC locations. White circles are locations determined from the local network (refer to Table 3) and scaled by network magnitude as in Fig. 1 (M_b range is 3.5-4.2).
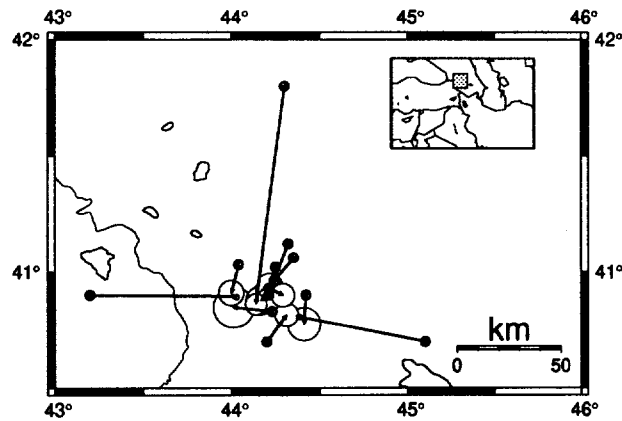

Figure 4. Comparison of locations of aftershocks of the Spitak earthquake. Small shaded circles are ISC locations. White circles are locations determined from the local network (refer to Table 4 on the next page) and scaled by network magnitude as in Fig. 1 (M_b range is 3.0-4.9).

Table 4: Comparison of local network, ISC, and NEIC locations for aftershocks of the Spitak, Armenia earthquake (after Dorbath et al., 1992).

Event ID	Source	Origin Time (h m s)	Lat	Lon	Depth (km)	M_b	Origin time diff. (s)	Epicentral diff. (km)	No. of stations	Max. Az. gap (range)
881207a	network	08 06 26.4	40.85N	44.01E	4.89	4.9				
	ISC	08 06 29	40.83N	44.23E	16	4.7	2.6	18.6	48	162°-275°
	NEIC	08 06 28.1	40.903 N	44.396E	10	4.8	1.7	33.1	22	
881207b	network	08 57 03.5	40.89N	44.03E	4.2	3.0				
	ISC	08 57 06.3	40.90N	43.20E	10	4.4	2.8	69.7	8	5°-138°
	NEIC	08 57 06.1	40.936 N	43.209E	10	4.6	2.6	69.1	7	
881207c	network	09 28 37.5	40.81N	44.38E	6.34	3.0				
	ISC	09 28 52	40.70N	45.10E	10	4.4	14.5	61.9	8	350°-160°
	NEIC	09 28 51.3	40.69N	45.37E	10	4.6	13.8	84.5	5	
881207d	network	10 56 50.4	40.88N	44.21E	6.34	4.2				
	ISC	10 56 51	40.96N	44.24E	2	4.7	0.6	8.8	32	219°-303°
881207e	network	14 10 14.5	40.94N	44.22E	66.34	4.3				
	ISC	14 10 16.9	41.06N	44.35E	10	4.3	2.4	17.4	50	192°-270°
881207f	network	18 05 41.8	40.88N	44.16E	4.2	4.4				
	ISC	18 05 42	40.90N	44.21E	2	4.4	0.2	4.8	49	219°-295°
	NEIC	18 05 42.8	40.952 N	44.160E	10	4.6	1.0	8.5	13	
881207g	network	19 17 51.5	40.86N	44.14E	6.34	4.1				
	ISC	19 17 58	41.80N	44.30E	10	4.2	6.5	105.3	9	350°-156°
	NEIC	19 17 56.6	41.690 N	44.750E	10	4.4	5.1	105.5	5	
881207h	network	20 07 28.9	40.91N	44.22E	6.34	4.4				
	ISC	20 07 31	41.12N	44.32E	7	4.4	2.1	24.5	49	219°-269°
	NEIC	20 07 30.3	41.208 N	44.471E	10	4.6	2.4	39.1	13	
881208a	network	01 49 38.2	40.91N	44.00E	4.2	4.3				
	ISC	01 49 40	41.03N	44.04E	7	4.2	1.9	13.8	39	219°-255°
	NEIC	01 49 41	40.955 N	43.401E	10	4.3	2.8	50.6	10	

Table 4: Comparison of local network, ISC, and NEIC locations for aftershocks of the Spitak, Armenia earthquake (after Dorbath et al., 1992).

Event ID	Source	Origin Time (h m s)	Lat	Lon	Depth (km)	M_b	Origin time diff. (s)	Epicentral diff. (km)	No. of stations	Max. Az. gap (range)
881208b	network	07 46 00.4	40.78N	44.41E	6.34	4.6				
	ISC	07 46 03.3	40.90N	44.42E	22	4.8	2.9	13.9	105	228°-255°
	NEIC	07 46 01.4	40.874N	44.336E	10	4.6	1.0	12.6	37	
881208c	network	20 32 05.8	40.89N	44.20E	6.34	4.5				
	ISC	20 32 06.4	41.02N	44.25E	10	4.8	0.6	15.1	130	220°-266°
	NEIC	20 32 06.4	41.147N	44.206E	10	4.8	0.6	28.5	53	
881210	network	19 13 57.8	40.82N	44.31E	5.46	4.2				
	ISC	19 13 58.6	40.70N	44.20E	10	4.4	0.8	15.8	10	343°-112°
	NEIC	19 13 59	40.76N	44.08E	10	4.5	1.2	20.4	7	
881212	network	15 36 17.2	40.90N	44.29E	5.46	4.2				
	ISC	15 36 18.1	40.93N	44.21E	10	4.5	0.9	7.5	35	219°-295°
	NEIC	15 36 17.9	40.82N	44.26E	10	--	0.7	9.2	10	

Discussion

The epicentral difference between ISC, NEIC, and local network aftershock locations are compared in Fig. 5, where location data from Tables 1-4 are plotted as a function of the number of ISC or NEIC stations reporting for each event. (Usually, for smaller events where the only phase is the first P arrival, the number of defining phases will equal the number of stations, so I use the terms "number of stations" and "number of phases" interchangeably.) Events with more than 150 stations reporting generally show differences of 10 km or less when compared with local networks, so I have only plotted the data up to 150 stations to better represent what happens when few stations are used in the ISC locations. Figure 5 shows that when less than 50 stations are used in the ISC locations the differences with local network location determinations can become quite large, especially when the number of stations reporting is less than 20. Results are similar for the NEIC data, although they start to depart at 50-60 stations. The number of teleseismic stations reporting for a given event depends on the location of the event within the network and, consequently, shows quite a bit of variation with magnitude. Using the data for the three aftershock studies examined here, the ISC magnitude corresponding to 50 stations reporting is typically about M_b 4.4 - 4.5. This is closer to M_b 4.7 - 4.8 for NEIC locations. Thus we can assume from this study that events larger than about M_b 4.4 - 4.5 have ISC locations accurate to about 15 km or less. A somewhat larger magnitude is needed for similar accuracy for NEIC locations.
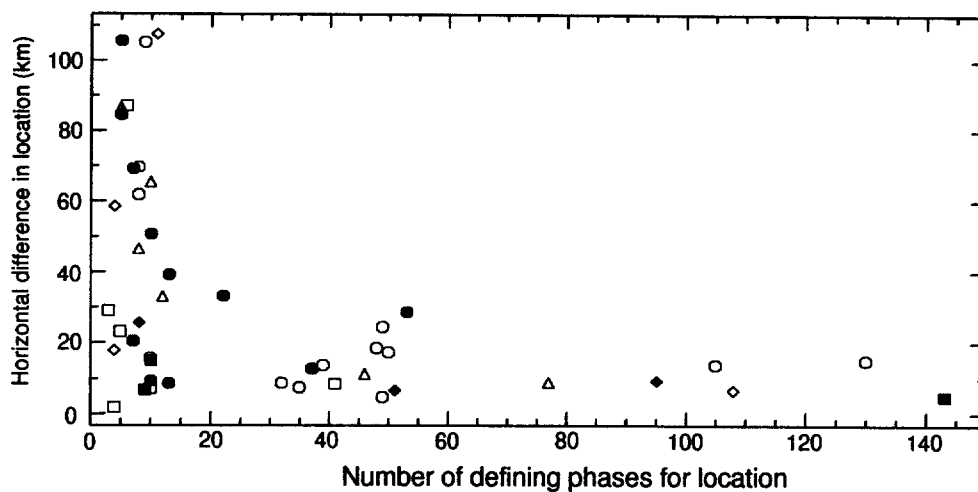
Figure 5. Location differences between ISC, NEIC, and the local networks as a function of the number of stations used in determining the event location. Open symbols are ISC determinations; solid symbols are NEIC determinations. Symbols are as follows: triangles - Tabas Iran, squares - El Asnam Algeria, circles - Spitak Armenia, diamonds - Zagros Iran.

The ISC depth determinations are much less reliable than the locations. For the Spitak earthquake (Table 4) the ISC depths showed shallow depths which were close to, but generally smaller or larger than the network determinations. In Armenia, the ISC depth determinations suggested shallow events, but the depth values were not reliable. In Iran, the ISC depth determinations were consistently much too deep, at least in the Zagros, and can not be considered reliable even for fairly large events. This probably indicates that the Jeffreys-Bullen velocity model is a poor fit to regional structure in Iran, but not as bad for northern Algeria. NEIC depth determinations seem to be slightly better than the ISC determinations.

Figure 6 shows the difference in depth between the local network and teleseismic determinations. NEIC determinations don't show a trend toward larger differences with fewer stations as the ISC data do. The biggest depth differences are for the Tabas aftershocks; as the number of stations reporting decreases, the teleseismic depth determination gets deeper. This agrees with the observations of Jackson (1980). Note that all of the aftershocks for these three aftershock sequences are shallow, being generally less than 15 km; the teleseismic depths are often listed as zero (refer to the tables).

Differences in origin time as a function of the number of phases (stations) reporting are shown in Fig. 7. Differences are generally less than 2.5 s until the number of stations is less than 50 or 60. NEIC determinations of origin time tend to be closer to those determined by the local networks than the ISC times are. In Fig. 8, the dependence of epicentral location difference on azimuthal gap is shown for the ISC determinations. The plot shows that fairly good locations (10-20 km) can be obtained with azimuthal gaps up to 200°, but very poor locations can also be expected when the gap is greater than 50°. Figure 9 illustrates the trade-off between origin time and depth. Most of the Armenia and Tabas data show that the depth determination difference will be about 1 km for each 1/3 second difference in origin time, as represented by the dotted lines in Fig. 9. This slope is similar to that determined for an Iran/Iraq earthquake analyzed by Billings et al. (1988).
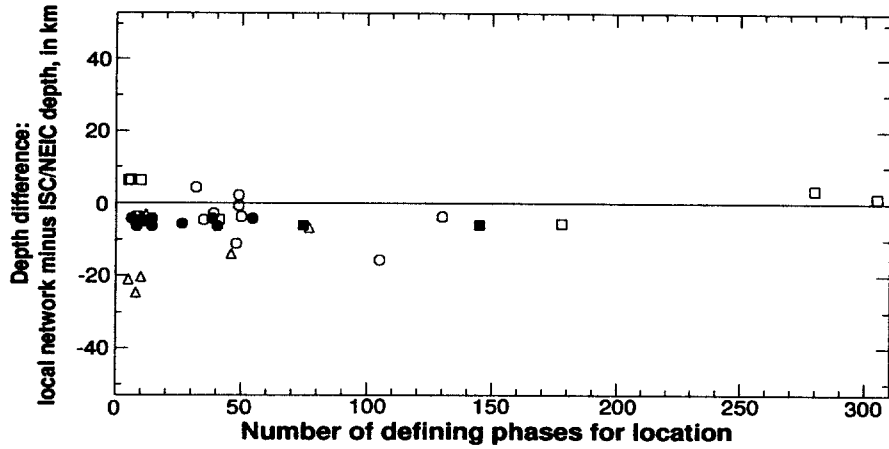
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Figure 6. Difference in depth determinations between ISC, NEIC, and the local networks as a function of the number of stations used in determining the event location. Open symbols are ISC determinations. Solid symbols are NEIC determinations. Symbols are as follows: triangles - Tabas Iran, squares - El Asnam Algeria, circles - Spitak Armenia. Zagros Iran depths are not included because the local network determination set the depth at 30 km for all events.
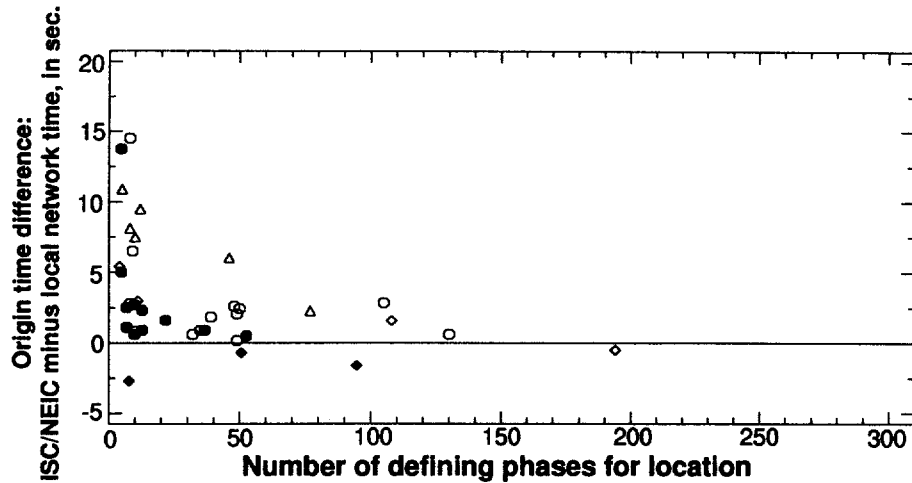

Figure 7. Origin time difference between well-located events and teleseismic determinations versus the number of stations (phases) used for the location determination. Solid symbols are NEIC determinations, open symbols are ISC determinations. Refer to data in Tables 1, 2 and 4. Symbols are as follows: triangles - Tabas Iran, circles - Spitak Armenia, diamonds - Zagros Iran. Accurate origin times were not available from the local network for the Algeria aftershocks.
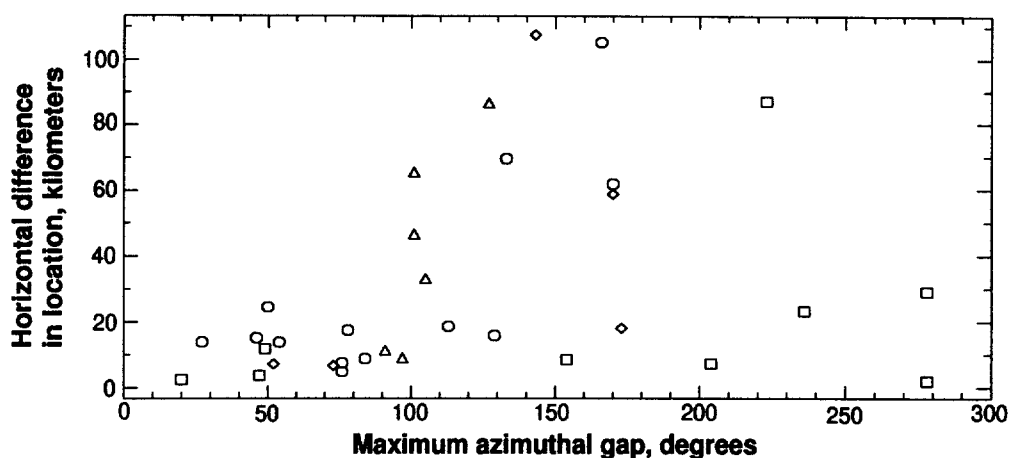
Figure 8. Difference in epicentral location versus maximum azimuthal gap for the ISC-located events of Tables 1-4. Symbols are as follows: triangles - Tabas Iran, squares - El Asnam Algeria, circles - Spitak Armenia, diamonds - Zagros Iran.
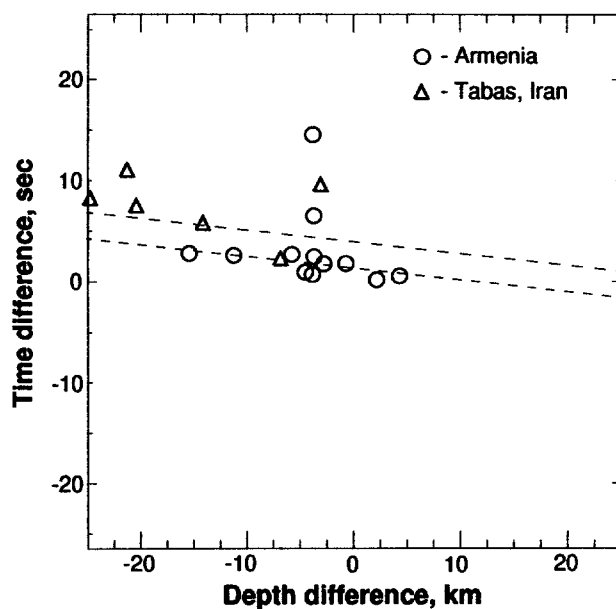

Figure 9. Origin time difference versus depth difference between the well-located events and the teleseismc determinations. Refer to Tables 2 and 4. Dotted lines have slopes (-0.33s/km) similar to those determined by Billings et al. (1988) for an event in Iran. Symbols are as follows: triangles - Tabas Iran, circles - Spitak Armenia. Accurate origin times were not available from the local network for the Algerian aftershocks and depths were fixed at 30 km for the Zagros Iran local network determinations.

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Based on the above findings, I performed one additional test of the accuracy of teleseismic locations by looking at P_n travel times from the ILPA data. Figure 10 compares the reduced travel times for 127 events recorded by ILPA during 1978 and 1979. Distances in Fig. 10 are determined from the ISC locations for each event, and the data is separated into groups with greater than or less than 40 stations used in the location. The cluster of data at a distance of 600 -700 km is mainly from aftershocks of the Tabas-e-Golshan earthquake. Better located events (with > 40 stations) within 600 km show much less scatter in reduced travel time than the poorly located events (with < 40 stations). For distances > 800 km, the reduction in scatter for better locations is not obvious; this may be because travel time differences caused by crustal structure variations play an increasingly greater role as distance increases.
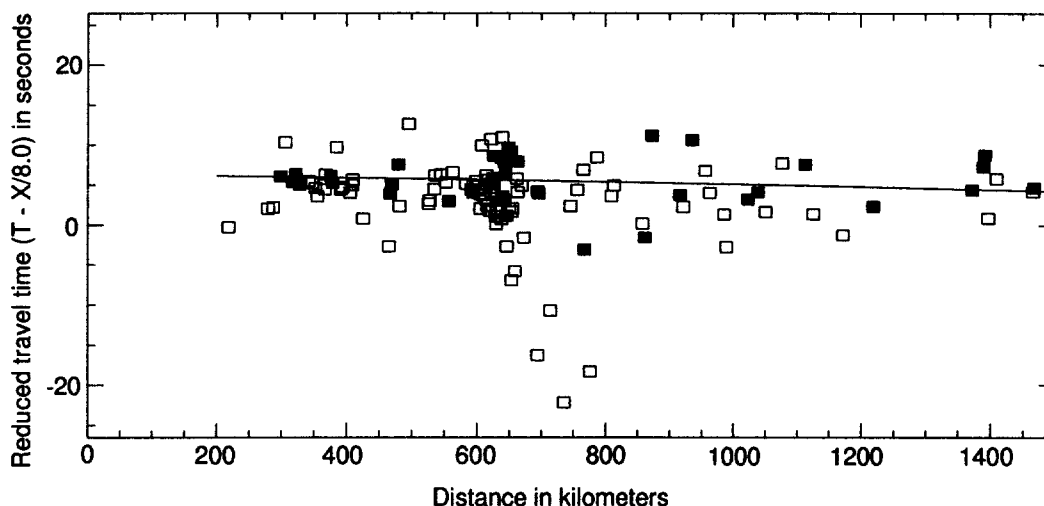

Figure 10. Reduced travel time plot for Pn travel times from the ILPA data set. Solid symbols are events located by the ISC with for 40 or more stations used. Open symbols are events located by the ISC with less than 40 stations. The solid line is the reduced travel time for the IASPE91 model with a source depth of 10 km and P_n velocity 8.1 km/s.

The importance of this study for regional seismic characterization is that it defines the level of confidence for ISC teleseismic locations in the Middle East and North Africa region. Based on this study, we should rely only on teleseismic locations with 40-50 stations reporting or events with magnitude greater than ISC M_b 4.4 - 4.5 (NEIC M_b 4.7 - 4.8) for accurate locations of events. Depth determinations will be suspect, even for large events, in the Zagros region unless a high percentage of the stations also include depth phases. In other areas ISC depth determinations are probably better than in Zagros, but should be approached with caution. The aftershock data used in this study also provide excellent ground truth for use with local and regional studies of travel times, attenuation, etc. where waveform data are available.

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Acknowledgments

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